

## A REVIEW OF MACHINING CHARACTERISTICS IN MECHANICAL DRILLING OF SUPER ALLOYS

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### ABSTRACT

*Super alloys are extensively used in the field of aerospace to manufacture aircraft engine components such as casings, rings, seals, fasteners, turbine blades, vanes, discs, shafts, combustors and general engine hardware. Drilling is a very important process that is mainly used to make a hole in the aircraft engine components. The quality of the drilled whole characteristics is of prime importance in the development of aero-engine components. This study reviews the machinability of drilling of super alloys during drilling through various aspects such as cutting environment, tool materials and geometry, drilling parameters and their influences on surface roughness, cutting force, tool wear, temperature, surface integrity, and chip morphology. The results indicated that very few studies have been made on the machinability of super alloys during drilling with respect to surface integrity. Further, there is a need to create a multi response optimization in the drilling of super alloys to obtain optimum results of surface integrity, thrust force, temperature, tool wear, surface roughness, and chip morphology.*

**KEYWORDS:** Super Alloys, Drilling, Dry Drilling, MQL Drilling, Nano Environment, Drilling, Tool Wear, Force & Surface Integrity

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### INTRODUCTION

Nickel based super alloys are mostly used to make aircraft engine due to high fatigue, creep resistance and corrosion & oxidation resistance at elevated temperatures and superior mechanical properties. As the aerospace components suffer extremes of temperature and pressure, quality controls of the highest order are required when parts are machined. The machining of these super alloys is difficult due to high work hardening and low thermal conductivity and these will affect surface and sub-surface quality, metallurgical alterations and dimensional accuracy and durability of the machined component made up of super alloys [1].

The modern machine tool concepts, advanced machining processes and methods such as technology integration, simplified operations route, process modeling and cutting strategy to predict part distortion, FE modeling, process & machine tool condition monitoring, green button process design, in-cycle probing and adaptive machining and high speed multi functional 5-axis machine platform are key enablers to achieve overall quality and productivity goals to meet future market requirements. [2]

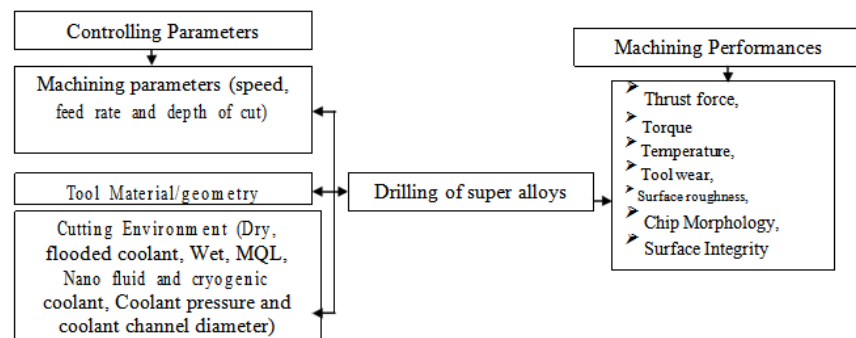
Drilling is a very important process and is mainly used to make holes in the aircraft engine components. Therefore, it is necessary to develop a procedure to select the appropriate cutting parameters and to optimize the

machining parameters in the drilling of super alloys. **Figure 4** shows the machining parameters considered while drilling super alloys. The factors such as speed, feed rate, and depth of cut, drill tool material / geometry and cutting environment must be carefully selected to obtain the best performance in the drilling of super alloys. Hence, the present paper aims to review the machinability of super alloys during drilling.

## EFFECT OF CUTTING ENVIRONMENT

The method of applying cutting fluid using MQL (Minimum Quantity Lubrication) has great effect on machining performances as this system uses the atomizer. Nano fluids possess enhanced thermal conductivity and heat transfer coefficient and the method of applying nano fluids using MQL system has great advantages, as this system has cooling effects with good penetration at the drilling interface [3]. The industrialists are forced to reduce the use of mineral oil-based

Metal working fluids as cutting fluids and it was reported that the vegetable oil-based fluids could be an environmentally friendly mode of machining [4].

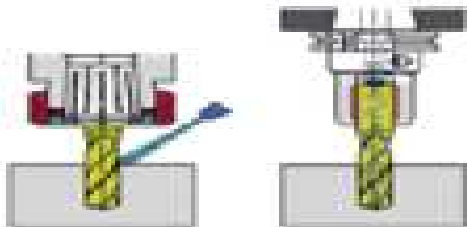


**Figure 1: Machining Parameters Considered in Drilling of Super Alloys**

Shokrani et al [5] stated that the machining of aerospace materials is usually associated with low thermal conductivity, poor surface quality and short tool life and stated that the environmentally conscious machining techniques reduced or eliminated the use of the conventional cutting fluids in material cutting operations. Machining operations are primarily expected to obtain lower machining costs, to improve quality of product and increase productivity. The cutting fluids improve the productivity of machining operations and nano fluids have strong temperature dependent thermal conductivity at very low particle concentration and they increase wettability, reduce cutting forces with low toxic [6]. Rahim and Sasahara et al [7] They investigated the effect of high speed drilling on machining characteristics of surface integrity of Inconel 718 while using TiAlN coated carbide drill tool under a minimum quantity of lubrication (MQL) environment. They observed that the cutting temperature increased with increasing cutting speed and thrust force and torque decreased linearly with increasing cutting speed but increased with increasing feed rate.

Erween et al [8] investigated the surface integrity during drilling of Inconel 718 under MQL machining environment while using palm oil and synthetic ester and they reported that the best machining performance was observed while using the palm oil on microhardness, surface roughness, surface defects and sub-surface deformation. EkremOezkaya et al [9] investigated the influence of the flux on the internal cooling without changing the pressure by using two different cooling channel diameters and observed that the higher mass flux and modification of channel diameters did not affect the tool life and bore quality and further reported that only higher coolant pressure improved tool

life. Further, they stated that the best results were observed when using higher coolant pressure of 60 bar. Sujan Debnath et al [10] suggested that the green manufacturing methods such as vegetable-based cutting fluids, dry cutting, minimum quantity lubrication (MQL), and cryogenic cutting could be some of the sustainable solutions from the environmental point of view. Muhammad Imran et al [11] conducted drilling operations on Inconel 718 alloy and studied the tool wear progression in relation to tool edge radius and under formed chip thickness. Further, they constructed wear map to identify an operating window of cutting conditions and also to identify the zones of lowest wear rate. Sunday Albert Lawal et al [12] reported that the MQL technique could be classified into two groups, namely internal supply of the medium via channels built into the tool and external supply via nozzle fitted separately in the machine. Figure.1 shows the differences between the MQL technique of external and internal feeds in drilling operations in which it is observed that the pressurized air and cutting fluid are mixed into the nozzle by a mixing device. Figure.2 shows the modified drill bit used in the MQL technique.



**Figure 1: External and Internal Feeds**

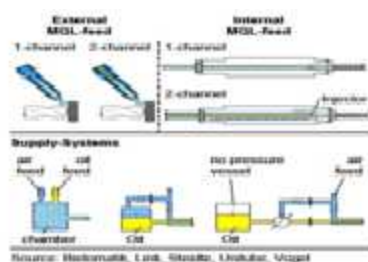


**Figure 2: Modified Drill Bit for MQL**

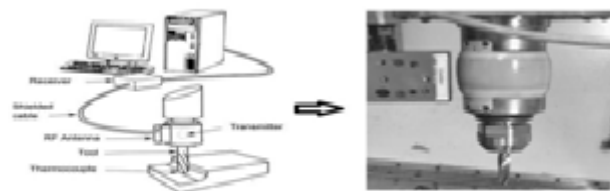
Weinert et al [20] reported that MQL would be the key to successful dry machining and they also stated that the external supply of fuel would be appropriate only up to length to diameter ratios of  $l/d < 3$  in drilling, reaming and tapping operations. The internal supply system was suggested in drilling, reaming and tapping operations with larger  $l/d$  ratio and the MQL feed system is shown in Figure.3. Le Coz. G et al [13] proposed a new temperature measuring system for rotating cutting tools. An acquisition system to which the temperature signals are transmitted, a data conditioning system and an RF antenna placed in the tool holder complete the measuring system and is shown in Figure.4. They performed drilling operations at different cutting conditions on aerospace alloy under MQL systems and observed thrust, torque, and temperature. They reported that drilling temperature varied from 590 to 640°C, torque increased with feed from 3.3 N. m to 5.4 N. m and a small increase of the cutting speed from 30 to 35 m/min led to an increase of temperature, for all the feed values.

Rachid M'Saoubi et al [14] reported that the machining of super alloys without coolant resulted in severe plastic deformation zones when drilling Inconel 718 alloy and it reveals the changes in the orientation of the grains and severe plastic deformation. Muhammad Imran et al [15] reported that the cutting conditions and the cutting temperature significantly affected the surface, sub-surface layers and tool wear. The wear occurred in wet cutting only on flank face and in dry cutting, on both flank and rake faces indicating a significant sticking and sliding action on the flank and rake faces. Soo et al [16] conducted drilling operation on RR1000 nickel-based super alloy under dry and wet conditions and they reported that the flank wear did not exceed 100  $\mu\text{m}$  when drilling at different conditions and holes surfaces showed hardened layers with adhered chips, material drag. The thick white layers present on the hole subsurface, when drilling in dry cutting and the use of the cutting fluid (preferably through spindle) ensure hole integrity.

Chen and Liao et al [17] investigated the tool life and wear features in drilling Inconel 718 while using TiAlN coated carbide drill tool. Further, they conducted experiments to identify the usable life in terms of holes that can be drilled while using coated and uncoated drill tool and reported that the coated drill tool improved usable tool life. However, the coated drill tool abraded off and thus increased the frictional force. They also investigated the tool life in the drilling of this alloy while using nano modifier fluid and observed increased tool life, low flank wear and high surface finish. Dixt et al [18] stated that, the cutting fluids were classified into two types, viz., neat oils (mineral oils and used for the metal cutting without further dilution) and water-mix fluids. The method of applying the cutting fluid using an MQL system had great effect on machining performance. Nano fluid is supplied to the machining area with MQL system in the form of mist mixed with highly pressurized. Nano fluid contains carbon nano tube (CNT), TiO<sub>2</sub>, Al<sub>2</sub>O<sub>3</sub>, MoS<sub>2</sub>, and diamond and the size of the nano particles is between 1 and 100 nm.



**Figure 3: MQL Feed System**

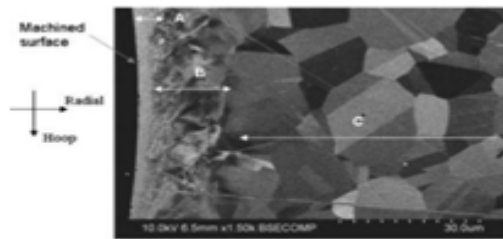


**Figure 4: Tool Holder, RF Antenna and Data Acquisition Diagram for Temperature Measurement**

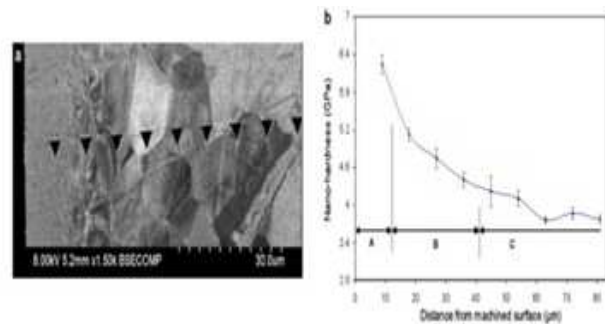
Shokoohi and Shekarian [19] reviewed the influence of cutting parameters on the responses such as cutting force, surface roughness, machining temperature and environmental effects and they also reported on the utilization of nano fluids in drilling and stated that the optimum utilization of nano fluids improved the performances of machining operations. It can be concluded that the cutting fluid type and method of applying the cutting fluids can influence the machining characteristics in the drilling of super alloys and the cutting fluids improve tool life and integrity.

## **EFFECT OF MACHINING PARAMETERS, DRILL TOOL MATERIAL AND DRILL TOOL GEOMETRY**

The typical tool wear mechanisms found by many researchers such as abrasive wear, adhesive wear, diffusion wear, chemical wear and plastic deformation. However, the adhesion, wear mechanism is the most prominent cause of tool failure [20]. Electrical discharge machining (EDM) is widely used in industries for micro drilling, however, mechanical micro-machining is considered for improved surface integrity and geometrical definition. They analyzed the drilled hole samples near machined surface and revealed three zones such as an ultrafine grain structure layer, a deformed grain structure layer, and the parent material represented by A, B, and C respectively as shown in Figure.5. They observed that the microstructure of layer A was so fine and layer B extended around 20–25  $\mu\text{m}$  from the machined surface and exhibited a deformed grain structure and the microstructure in layer C was characteristic of the parent material. They also carried out Nano-indentation across the three layers (A, B, C) zones as shown in Figure.6. The hardness rose in layer B compared with the bulk value and it could be attributed to the increased work hardening arising from the deformation associated with zone B. The hardness in zone A was significantly high due to a rise from a combination of the ultra-fine nano crystalline grain structure and the higher dislocation activity [21].



**Figure 5: (Backscattered Electron) Image Showing the Surface and Subsurface Layers at 5,000 rpm and 5 µm/rev**



**Figure 6: A) Position of Nano indentation at Various Altered Layers of the Work piece B) Nano indentation Profile across the Three Different Zones at Feed Rate of 2 µm/rev and at Speed of 3,000 Rpm**

Turgay Kivak et al [22] investigated the hole quality and tool wear during drilling Inconel 718 with coated and uncoated carbide drills and they observed increase in deviation from circularity and hole diameter with increase in cutting speed and feed rate. They reported that as the cutting speed increased, the corner wear and flank wear increased in the uncoated drill bit and the tool wear occurring at low feed rate and led to a chisel edge wear as feed rate increased. Sharman et al [23] used multilayer coated drills (TiAlN, TiAlN, TiN/TiAlN, TiAlN) having curved cutting edge tool, straight cutting tool and concave cutting edge tool, and they observed that drills with curved cutting edge gave superior performance in the drilling of Inconel 718. Dahu Zhu et al [24] identified some of the research gaps such as less work considering the significance of machining characteristics brought by the physical and chemical properties, which directly results in poor prediction accuracy and the current research on the coated tool wear is rarely associated with the diffusing layer of tool coating/substrate.

Ali Riza Motorcu et al [25] evaluated the surface roughness, chip formation and tool wear in the drilling of Waspaloy super alloy and they reported that the surface roughness values reduced with an increase in speed from 17m/min to 20 m/min and tool wear rate also increased as the machining time duration increased. Further, they observed that the surface roughness value was 1.0 µm at the feed rate of 27 mm/min and it stood at the value of 1.20 µm at medium feed rate of 32 mm/min. It was also observed that the highest surface roughness value was 1.13µm at the drill bit angle of 142°. Dirk Biermann and Marko Kirschner [26] reported that an optimized and tailored tip design was suitable to obtain favorable chip formation, sufficient bore quality, less tool wear and stable process productivity in gun drilling of Inconel 718. At a cutting speed  $v_c=30$  m/min and a feed rate  $f = 5$  µm the mean value of the drilling torque was about 20% less using the optimized tip design and the chips were characterized by a short chip length, strong curling and built chip along the major cutting edge. Nicolas Beer et al [27] reported that, the use of a modified drill by modifying the flank face with a groove, leads better coolant supply, improved bore quality and improved tool life due to the fact that the width of the flank wear land is limited and a wear stock is achieved by the groove. Hooda et al [28] performed drilling operation on Haynes 282 aero engine material by using coated carbide tool with high pressure cutting fluid. They observed that surface and subsurface microstructural damage was confined to bend or deformed grain boundaries up to a depth of 15 µm and discontinuous white layers up to 6 µm thick from the workpiece surface.

Cuesta et al [29] investigated the thermal and mechanical loads affecting in the drilling of Inconel 718 at different cutting conditions during dry and lubricated condition. They measured the temperature by IR (Infrared Thermography) technique and by means of a piezoelectric dynamometer. They observed the maximum values of torque and specific

cutting force ( $K_s$ ) with lowest cutting speed of 15m/min and maximum feed of 0.2mm/rev regardless of lubricants. The lowest feed force and torque were observed at the highest cutting speed of 30m/min and the lowest feed of 0.1mm/rev. Further, they observed that the specific cutting force decreased when cutting speed increased at constant feed rate and stated that it would be due to the reduction of the shear strength of the material caused by the increase of temperature in the cutting zone. They also reported that the temperatures measured in the lubricated tests decreased significantly compared with the dry drilling.

Kwong et al [30] investigated the surface sensitivity of new Ni-based super alloy RR1000 (Coarse grain RR1000, which is a unique combination of mechanical and thermal properties making it even more difficult-to-machine than the traditional Ni-based alloys), while drilling with self centering two fluted TiN/TiAlN coated drills with 30° helix angle at different levels of cutting conditions. They assessed the sensitivity of drilled surface in terms of Metallurgical analysis, Micro hardness, and Residual stress. They reported that a significant increase in micro hardness of 180HV was observed while drilling this alloy at high speed.

Herbert et al [31] stated that the metallurgical nature and structure in metal cutting is importance and they investigated the generation of white layers it in drilling of RR1000 super alloy. They reported that the white layer is FCC in structure with average grain size of 50nm compared to bulk material of 22-63µm. It is also observed that, the white layer veins formed at the surface and it is due a combination of material drag and high thermal influences and thickness of white layers observed is 3 µm. In drilling without coolant at high speed, high temperatures were noted at the tool-work piece interface resulting in the formation of a continuous of white layer material with a maximum measured depth of 5 µm and they were due to the low thermal conductivity of RR1000. Further, they reported that the residual stress was all found to be tensile in the hoop direction and, for the high speed and high wear conditions the combination of thermal and mechanically induced stresses extended to a depth of around 100µm beneath the surface. In the axial direction, compressive residual stresses of -1000MPa were measured. Finally they concluded that material removal rate and tool flank wear must be maintained within control to maintain whole integrity. Andre Popa et al [32] performed drilling operations on Nickel based super alloy (INCONEL 718) at different cutting conditions and observed the surface integrity of the drilled hole. They reported that the main influential factors on the surface integrity were flank wear and cutting fluid emulsion.

Imran et al [33] compared EDM (Electrical Discharge Machining) with laser and mechanical micro-hole drilling of Inconel 718 alloy. They reported that mechanical micro-drilling produced improved mechanical, metallurgical and geometrical properties compared with both laser and EDM processes. The holes made by mechanical drilling exhibited improved surface integrity, surface roughness, roundness, no recasts and microcracks compared with EDM drilling; however, they exhibited tool wear and lower hole aspect ratios. Dutilh et al [34] established the relations through the cutting conditions between the process monitoring signals (4 components Kistler Dynamometer) and surface integrity anomalies. They also defined the domain of validation by combining the cutting conditions according to the criteria established by AFNOR E66-520 norm (couple -tool-material) and the criteria of surface integrity for drilling of Udimet 720 super alloy.

Kolahdoozan et al [35] investigated the effect of various cutting speeds (400 to 600 rpm), feed rates (0.1 to 0.14 mm) and tool diameters (5, 10, 15 mm) with constant depth of cut on tool wear in drilling Inconel 718 while using cement coated carbide tool (TiAlN). They developed a model by using Minitab and FEA to predict the tool wear and compared with tool wear obtained by experimental and reported 4-6% percentage error among model values and experimental values.

Further, they had identified that increasing cutting speed and feed rate resulted in high tool wear rate according to experimental and FEA analysis. They used DEFORM-3D FEM software and 3D Lagrangian finite element model. Marek Vrabec et al [36] conducted drilling operations on nickel based super alloy UDIMET 720. They reported that the designed and tested network model with 3-5-1 achieved satisfactory results for the prediction of tool wear with the average RMS error percentage of 12.7% and the designed and tested network model with 4-6-4-1 achieved satisfactory results for the prediction of surface roughness with the average RMS error percentage of 2.64%.

It is evident from the above review of relevant studies that the surface roughness, hole circularity, integrity, torque and thrust force etc., are mainly dependent on the cutting parameters, cutting environments, geometrical parameters of the tool, machining time, physical & chemical properties and tool material in the drilling of super alloys.

## CONCLUSIONS

It can be concluded that the research work carried out on the drilling of super alloys was restricted to Inconel 718 and there is a need to carry out the research work adequately on other super alloys such as Nimonic alloys, Waspaloy, Udimet alloys and Monel etc. There is also a need for a comprehensive study on soft computing applications such as artificial neural networks (ANN), grey fuzzy optimization, non dominated sorting genetic algorithms (NSGA-II), fuzzy rule based model and finite Element Analysis (FEA) as applied to the drilling of super alloys for predicting the process parameters. Further, there is an urgent need to develop 'multi-response optimization' of machining parameters to get optimum machining performances.

The following conclusions were drawn with regard to the drilling of super alloys:

- Vegetable-based cutting fluids, dry cutting, minimum quantity lubrication (MQL), cryogenic cutting and Nano fluids are some of the sustainable machining-cleaner, safer and environmental-friendly.
- Higher coolant pressure improves tool life.
- Machining of super alloys without coolant resulted in severe plastic deformation Zones.
- White layers present on the hole subsurface in the drilling of super alloys under dry conditions. However, the use of cutting fluid ensures integrity.
- Increased tool life, low flank wear and improved integrity while drilling using Nano-modifier fluid are possible.
- Abrasion, Adhesion and Micro-chipping are dominant wear mechanisms.
- Deviations in hole circularity and hole diameter were observed with increase in cutting speed and feed rate.
- At high cutting speed and feed rate, high temperature with formation of white layer, high tool wear and micro hardness were observed.
- Mechanical micro-drilling improved integrity, surface finish and no recasts and no micro cracks were observed compared with EDM and Laser drilling.
- Long continuous chips, low chip size, low torque and improved tool life were observed in ultrasonic assisted drilling.



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